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6. AUTHOR(S)
Glen G. Gawarkiewicz

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
Woods Hole Oceanographic Institution
Grant and Contract Services
221 Oyster Pond Road
Bell House MS 39
Woods Hole MA 02543-1531

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9. SPONSORING / MONITORING AGENCY NAME(S) AND ADDRESS(ES)
Theresa Paluszkiewicz
Office of Naval Research
875 North Randolph Street
Arlington, VA 22203-1995

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14. ABSTRACT
We performed a custom climatology of the northern South China Sea, Taiwan Strait, and the Kuroshio east of Taiwan using the historical hydrographic archives of Taiwan. This work was performed jointly with scientista at National Taiwan University. The climatology focuses on the thermohaline and soundspeed fields over the outer shelf and continental slope and are seasonal. Important features which were resolved were the shelfbreak current system in the northern South China Sea, the coastal current passing southward on the western side of Taiwan Strait, and the northward flow of Kuroshio water in Taiwan Strait on the eastern side of the strait. In addition to the climatology, several research cruises were performed examining the stratification over the outer shelf and upper slope and processes occurring where the seasonal pycnocline intersects the bottom over the shelf, and the Kuroshio in Luzon Strait. In collaboration with National Taiwanese University colleagues, a stability analysis of the Kuroshio in Taiwan Strait indicates frontal instability can account for variability observed in a mooring array.

15. SUBJECT TERMS
South China Sea, continental shelf processes, shelfbreak, Kuroshio, Luzon Strait

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Integrated Studies of Oceanographic Processes and Shallow Water Acoustics in the South China Sea: Custom Climatology and mid-shelf Field Work

Glen Gawarkiewicz
Department of Physical Oceanography
Mail Stop #21
Woods Hole Oceanographic Institution
Woods Hole, MA 02543
Phone: (508) 289-2913 Fax: (508) 457-2181 email: gleng@whoi.edu

Long-Term Goals

The long-term goal of this project was to understand oceanographic processes and variability in currents and thermohaline structure in the northern South China Sea. In collaboration with acousticians, we also attempted to quantify the effect of different oceanographic processes on low-frequency acoustic propagation in this area.

Objectives

Our specific objectives were to develop a shelfbreak centered climatology of the outer continental shelf and continental slope for the northern South China Sea and to examine processes contributing to variability of the shelf and slope in this area. We wanted to use the climatology to examine cross-shelf mean gradients in temperature, salinity, and density near the shelfbreak. Our objectives in studying the variability of the region were to establish the role of Kuroshio Intrusions in affecting slope circulation in the northern South China Sea and to examine processes causing the Kuroshio Intrusions.

Approach

For the climatology, we collaborated with Dr. David Tang and Ph.D. candidate Jen-Hua Tai. Using a technique developed by Linder and Gawarkiewicz (1998) and Linder et al. (2006), we used the Taiwanese historical hydrographic data archive which included both hydrographic data as well as shipboard Acoustic Doppler Current Profiler (ADCP) data to develop two dimensional cross-shelf mean and standard deviation fields relative to the shelfbreak. This is an important task because the circulation in the northern South China Sea is complicated and affected by the seasonal monsoons as well as Kuroshio Intrusions into the South China Sea via Luzon Strait. As part of this effort, Jen-Hua Tai was a guest student at WHOI for a year.

In order to study synoptic variability, we used a variety of approaches. In one study, we used a combination of remotely-sensed sea surface temperature data along with in situ hydrographic data to study the structure of Kuroshio Intrusions into the South China Sea. We also participated in joint cruises with Taiwanese investigators from National Taiwan

University to examine the stratification over the outer shelf where the seasonal thermocline intersects the bottom in April, 2005 and the structure of the Kuroshio in Luzon Strait in August, 2007. The latter cruise along with Jen-Hua Tai's visit to WHOI motivated a study of the impacts of ridge topography on the stability characteristics of the Kuroshio in Luzon Strait. This work formed the basis of a Ph.D. thesis which is nearing completion at this time.

Tasks Completed

We have completed the climatology and have submitted a manuscript on this work (Linder et al, 2009). A study on the variability of the Kuroshio Intrusion using the satellite-based Sea Surface Temperature data and ASIAEX hydrographic data has appeared (Caruso et al., 2006). A study of the acoustic propagation from April, 2005 including the impact of internal tides has been completed (Emerson et al., 2007). A study of the character of frontal waves on the Kuroshio in Luzon Strait and a stability analysis of the Kuroshio has been finished and a manuscript has been submitted (Tai et al., 2009). Analysis of the internal tides on the outer shelf in April, 2005 will be presented at the Ocean Sciences Meeting in February, 2010.

Results

The interannual variability and structure of Kuroshio Intrusions into the South China Sea was examined in Caruso et al. (2006). Both remotely sensed sea surface temperature and sea surface height anomaly fields were examined for the time period 1997-2005. In situ observations from the ASIAEX field program (SeaSoar data from the central basin of the South China Sea were also analyzed for further insight into the structure of the Kuroshio Intrusions. Three major types of intrusion were identified. The first was representative of mean winter conditions, with the Kuroshio extending westward into the South China Sea. This type of intrusion does not result in significant transport of Kuroshio water masses west of 120.5° East. The second type has a velocity maximum in the southern portion of Luzon Strait. This type of intrusion is quite complex as it may result in a branch current extending to the southwest along the shelfbreak, an anti-cyclonic loop current, and an anti-cyclonic loop current evolves into an eddy which detaches and propagates into the South China Sea. The third type of intrusion has a westward velocity maximum in the northern portion of Luzon Strait and is associated with a cyclonic circulation south of Taiwan. A schematic diagram of the different types of Kuroshio Intrusion appears in Figure 1. A particularly strong southern intrusion occurred in the winter of 1997-98 while a good example of a northern type intrusion occurred in 2002-2003. An Empirical Orthogonal Function (EOF) analysis of the sea surface temperature fields reveals that the majority of the variance is related to the seasonal heating and cooling cycle. However, the second mode is a combination of the northern and southern type Kuroshio Intrusions, with the third mode representing a longer-term cooling trend over the time period of the analysis.

The impact of oceanographic variability over the outer continental shelf and its impact on variability of transmission loss appears in Emerson et al. (2007). This study involved using high-resolutions surveys with a Scanfish towed vehicle and concurrent transmission loss measurements with an autonomous mobile acoustic source in combination with sonobuoys. Two different sources were launched in April, 2005, and exhibited similar transmission loss over bearings of 315° to 030°, but exhibited a 5 dB difference in transmission loss over a bearing of 067°. The orientation of the constant transmission loss was in the direction of propagation of internal waves, while the transmission loss differences were oriented along the orientation of the internal waves. Observations from a moored thermistor chain indicated that over the seven hours of the mobile acoustic source transmissions there were significant thermocline displacements associated with internal tides and the passage of internal wave packets. An example of the steepening of the internal tide appears in Figure 2.

We have computed a four season, two-dimensional climatology for both Taiwan Strait and the northern South China Sea, centered on the shelfbreak (Figure 3). We found a predominantly northeastward flow near the shelfbreak in the South China Sea, consistent with an anti-cyclonic gyre southwest of Taiwan. Maximum velocities over the upper slope are 40 cm/s. The maximum variability occurs just seaward of the shelfbreak in a depth range of 40 to 80 m for temperature, and near the surface at the shelfbreak for salinity. Transports, using mean barotropic velocities from all available shipboard ADCP sections, are at a maximum in summer (1.8 Sv) and at a minimum in spring (0.1 Sv). The seasonally averaged transports for both the shelfbreak in the northern South China Sea as well as Taiwan Strait appears in Figure 4. A web-based technical report which includes all the climatological fields was completed (Linder et al., 2006).

In Taiwan Strait, the dominant variability is present on the western side of the strait and is associated with the China Coastal Current. Maximum transport in the strait is to the north and is 1.9 Sv in summer (compared to previous estimates of 1.5 Sv) and a minimum of 0.4 Sv in spring, again northward. The mean and standard deviation fields appear in Figures 5 and 6.

J.-H. Tai is close to completing his Ph.D. degree at National Taiwan University after having spent a year at Woods Hole Oceanographic Institution working with G. Gawarkiewicz. He has completed an instability analysis of the Kuroshio over ridge topography and has compared his results to moored measurements in Luzon Strait. Both the moored observations and the model show northward propagation of Kuroshio frontal meanders with phase speeds of 35 cm/s. Growth rates were on the order of two days from the mooring observations. A two layer instability model based on an earlier model by Barth (1989) had slower growth rates but a model with continuous stratification (Xue and Mellor, 1993) did produce similar growth rates. The presence of the two ridges in Luzon Strait had a significant impact on the modal structures with increases in the perturbations in the lower layer near the crest of the western ridge. The basic state for the stabiltity models was chosen based on sections across the Kuroshio taken August, 2007 using the SeaSoar from National Taiwan University. A manuscript on this work has been submitted to the Journal of Physical Oceanography (Tai et al., 2009).

We are continuing analyze data collected in April, 2005 (Emerson et al., 2007) with emphasis on the internal tides. We have identified strong internal bores in the data and are presently examining the bore structure as well as boluses of cold water which appear on the shelf. S. Jachec of the Florida Institute of Technology visited WHOI in July, 2009 and worked on two-dimensional numerical model simulations of the strongly non-linear internal tides. This joint work will be reported at the Ocean Sciences Meeting in February, 2010.

Impact for Science

The suite of studies completed here has a number of important ramifications. First, the number of different types of Kuroshio Intrusions reported in Caruso et al., 2006 attests to the complexity of the flow within Luzon Strait and the possibility of multiple causal mechanisms for the intrusions. The intrusions impact the flow over a substantial area of the South China Sea. This study also identified long-term trends in sea surface temperature and chlorophyll *a* for the region as well as categorizing the dominant types of intrusion for the eight year period of analysis.

Second, the climatology shows the seasonal evolution of the thermohaline and density fields as well as referenced geostrophic velocities and potential vorticity distributions at the shelfbreak. The spatial and seasonal distributions of the variance of the fields give indications of "hot-spots" of variability. To the extent that models resolve the underlying processes causing the variability, these would also be expected to be areas of higher uncertainty for predictions of the soundspeed and velocity fields.

Third, the stability analysis of the Kuroshio in Luzon Strait suggests that instabilities may play an important role in the nature of the Kuroshio Intrusion formation. While further work is necessary, the stability models confirm the dominant space and time scales observed from the mooring array in Luzon Strait. Large amplitude meanders of the Kuroshio would be expected to affect the propagation of large-amplitude internal waves from Luzon Strait into the South China Sea as well as the predictability of the arrival time of wave packets in the South China Sea.

Finally, S. Jachec, in collaboration with G. Gawarkiewicz, has produced two-dimensional simulations of the internal tide structure near the shelfbreak based on conditions observed in April, 2005 with the peak stratification near the bottom over the shelf. The stratification was very different than that encountered during the ASIAEX experiment, when the peak stratification was very close to the surface (15 m depth). Thus the ongoing work enables us to understand a different range of conditions typified by much larger mixed-layer depths. We are also working on understanding the parameters which affect the formation of detached boluses of cold dense water which have previously been reported by Venayagamoorthy and Fringer (2007) from numerical simulations. Detached boluses were observed in April, 2005.

Relationships to Other Programs

The climatological tools developed here have been used in a number of other programs. During planning of the Quantifying, Predicting, and Exploiting Uncertainty DRI, climatological fields were produced for the East China Sea using both the software and data base developed by J.-H. Tai of National Taiwan University. We will also be using the climatological tools for analysis of nutrient distributions in the Middle Atlantic Bight for the ESPRESSO MURI on bio-optical properties in shelfbreak regions. The climatology technical report was distributed by ONR to a number of interested parties in the Navy.

This work was closely related to the DRI "Capturing Uncertainty in the Tactical Environment". Climatological tools were developed which were then refined in this project. Observations from 2005 were also used in related internal wave programs in the South China Sea by L. St. Laurent of WHOI and S. Jachec of Florida Institute of Technology.

Figures/Pictures

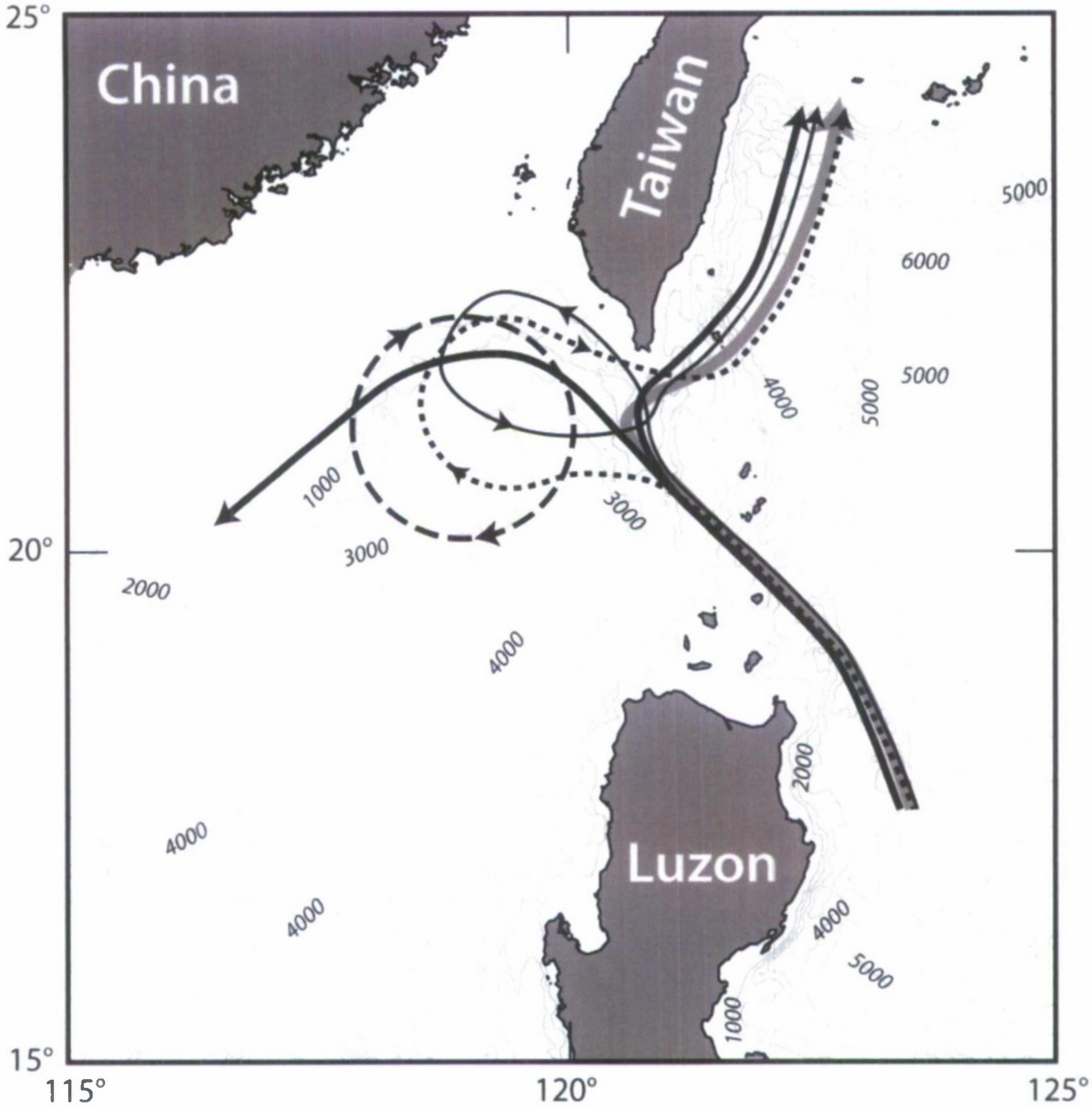

Figure 1: Schematic showing the different types of Kuroshio intrusions. Type 1 (grey) shows the mean position of the Kuroshio as it partially enters the Luzon Strait. Type 2a (thick, solid) shows the SCSBK entering and flowing southwestward along the shelfbreak. Type 2b (short dashed) is an anti-cyclonic loop current that penetrates into the basin before returning to the mean path. Type 2c (long dashed) is an anti-cyclonic eddy that has detached from a type 2b intrusion. Type 3 (thin, solid) enters in the northern part of the strait and forms a cyclonic circulation before returning to the mean path.

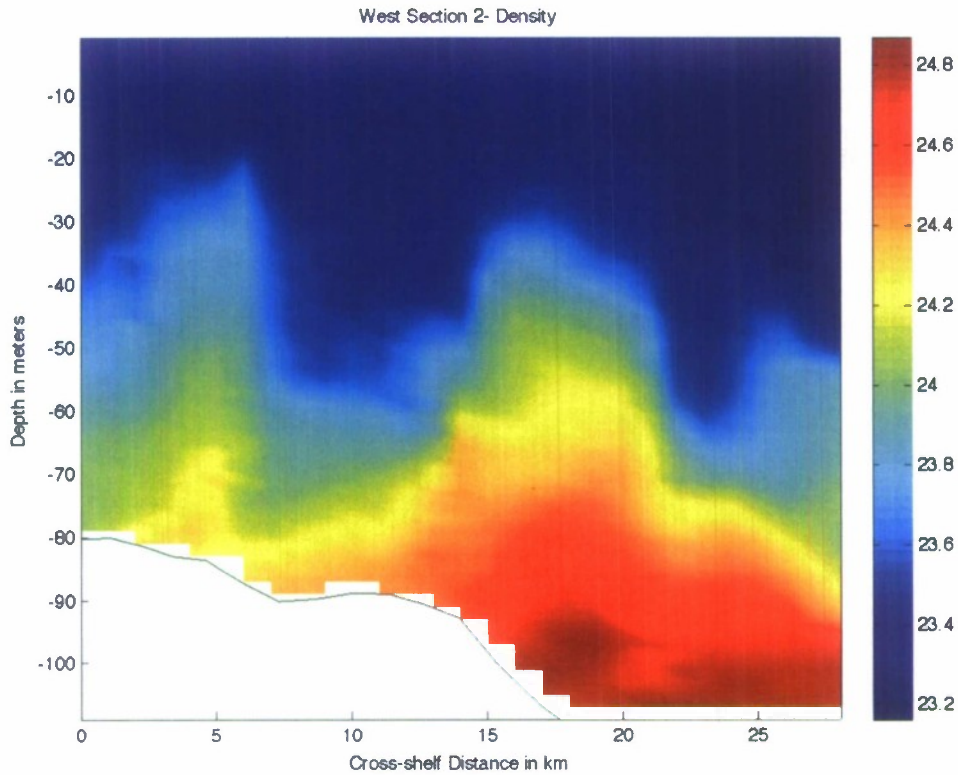

Figure 2- A section of density from the South China Sea in April, 2005, showing the steepening of the thermocline associated with the internal tide (x=15 km). Note the incipient formation of a detached bolus of dense (cold) water propagating into shallow water.

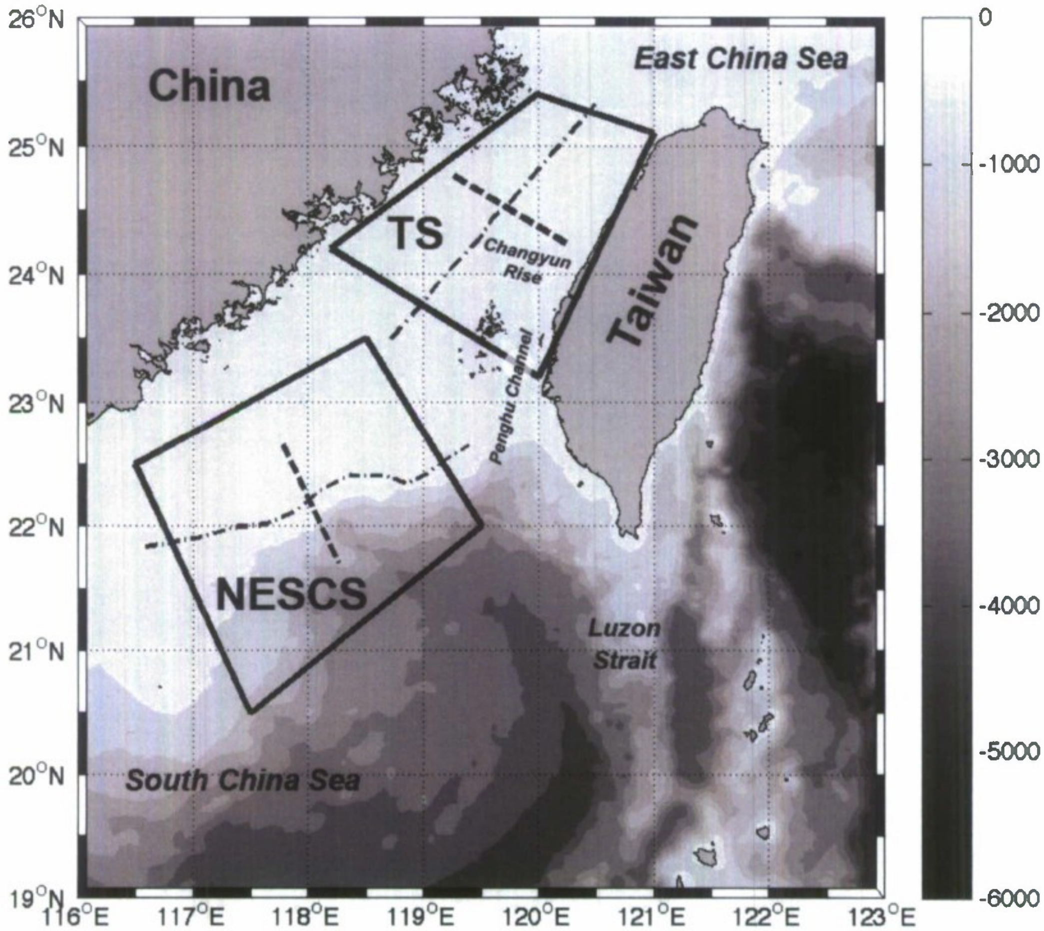

Figure 3- A map denoting the areas used for the climatological fields produced for the northern South China Sea and Taiwan Strait. All data from within the polygon is used and mapped relative to the reference bathymetry (light dashed line). The dark dashed line represents the cross-shelf (NESCS) and cross-strait (TS) section that the data is projected onto.

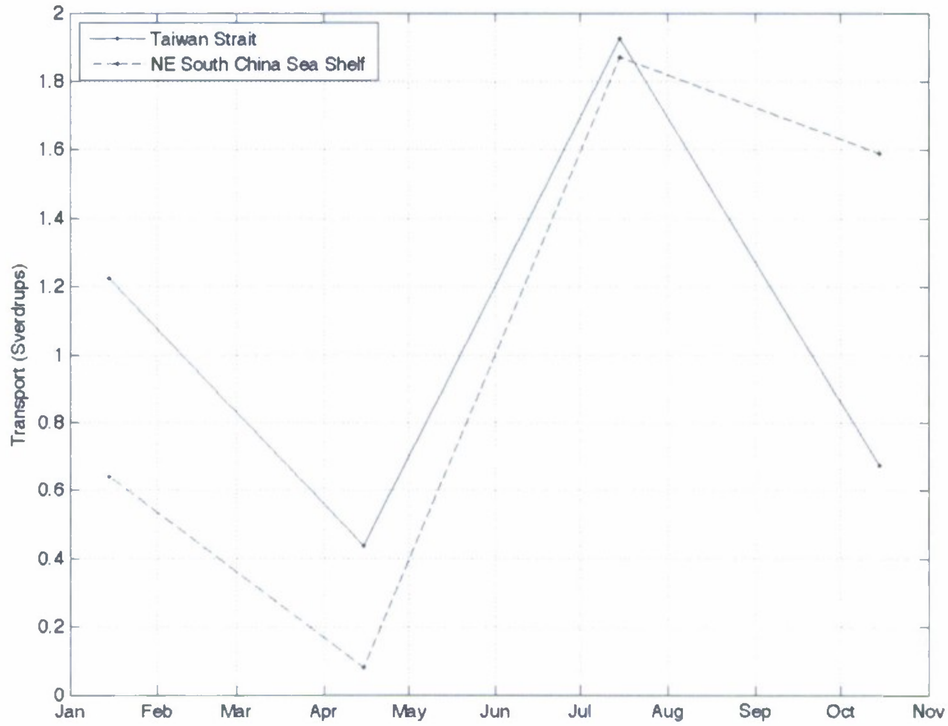

Figure 4- The seasonal variation in transport within the northern South China Sea (dashed line) and Taiwan Strait (solid line).

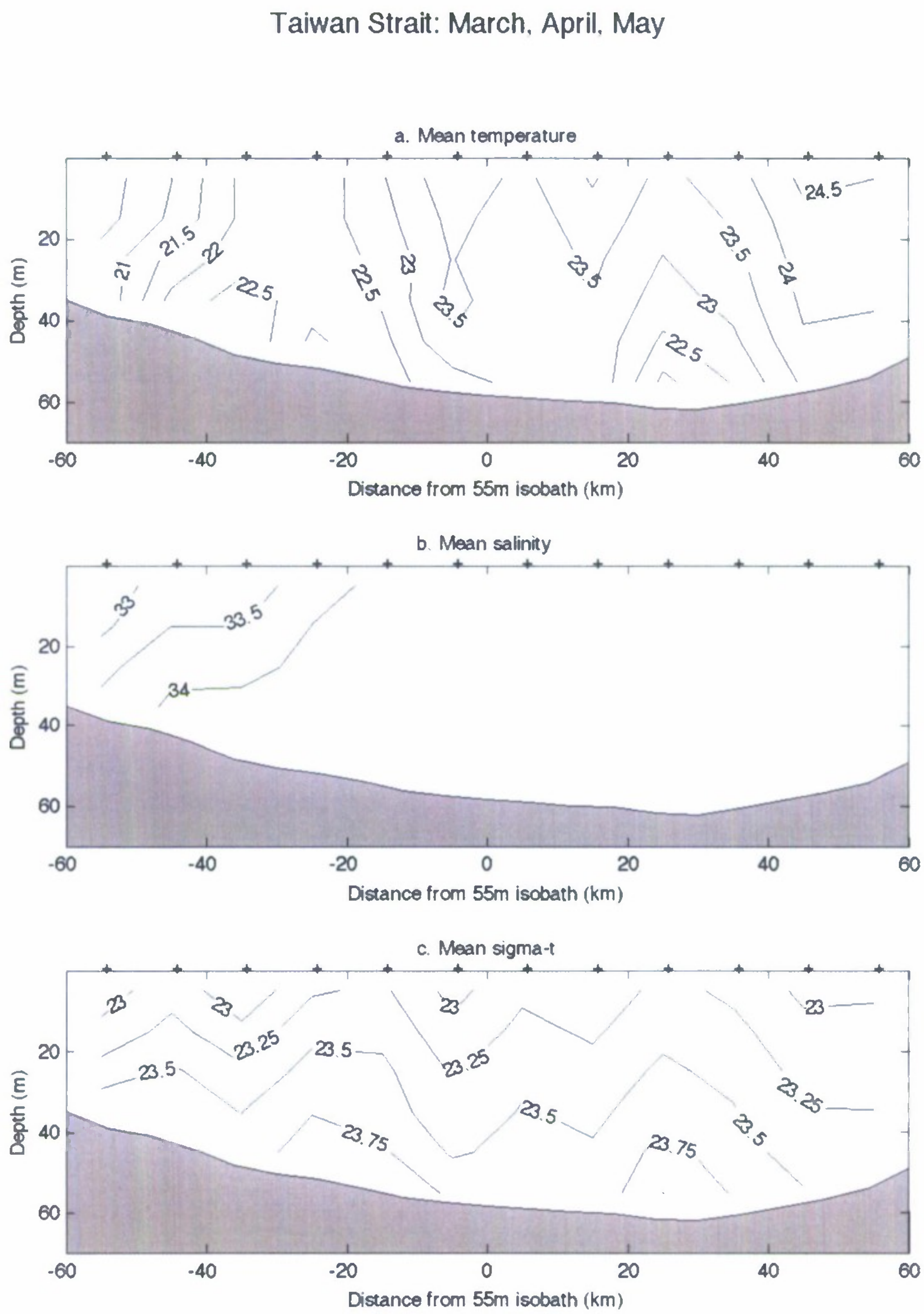

Figure 5- Mean fields of temperature (upper panel), salinity (middle panel), and density (bottom panel) for spring in Taiwan Strait. The bins used for averaging are denoted at the top of the panels. Note the presence of the China Coastal Current in the salinity field at the left side of the figure (western side of Taiwan Strait).

Taiwan Strait: March, April, May

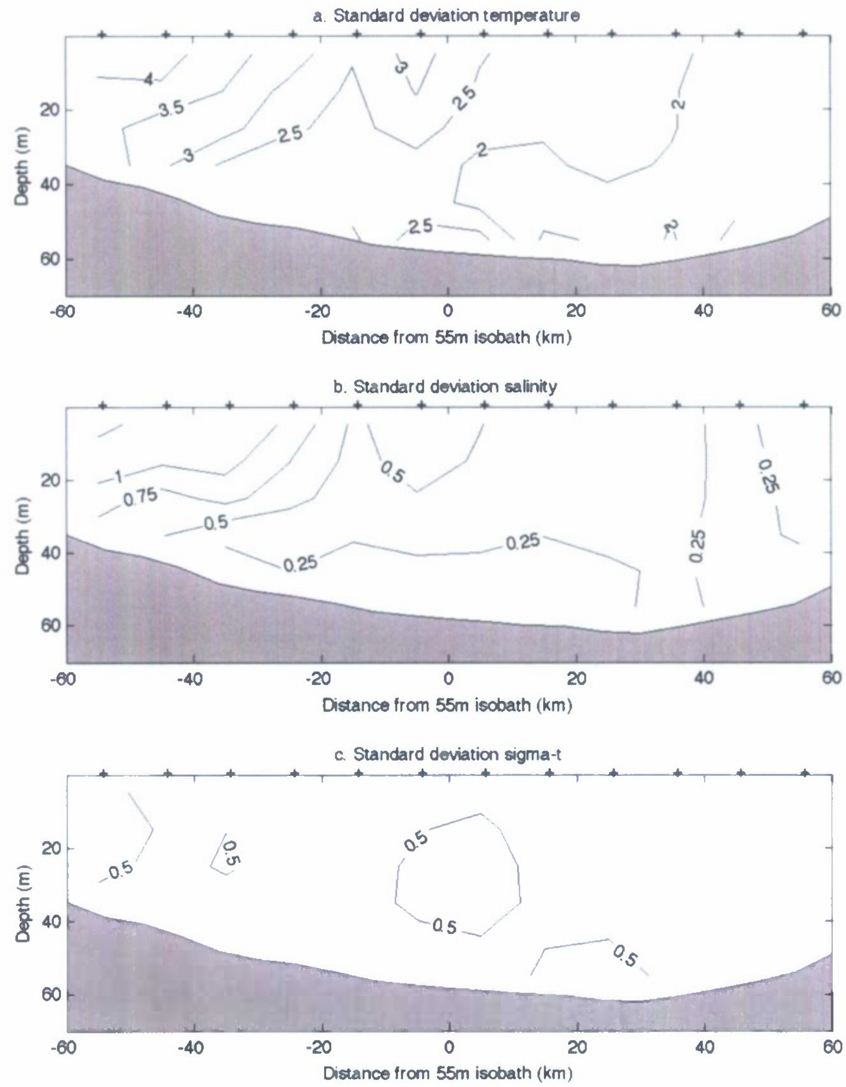

Figure 6- The spatial structure of the variability within Taiwan Strait as expressed in the standard deviation fields. The top panel is temperature, the middle panel is salinity, and the bottom panel is density. The maximum standard deviations appear at the western end of the strait and are associated with the China Coastal Current.

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